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13. ABSTRACT (Maximum 200 words)

In this project, we developed 3D models of temperature and wind velocity fluctuations in nighttime boundary layers (NBL) and, using these models, studied sound propagation and scattering.
The 3D spectra of temperature and velocity fluctuations due to internal gravity waves in moderately and very stable NBL were obtained. The 3D spectra of turbulent temperature and wind velocity fluctuations in weakly stable, intermittent NBL were modeled with the use of the von Karman spectra. Quasi-wavelet models of turbulent temperature and velocity fluctuations were developed.
The developed models of internal gravity waves, turbulence, and quasi-wavelets were then used for calculations of the statistical moments of plane and spherical sound waves propagating in the atmosphere. These calculations were done for three different problems: scattering of sound, line-of-sight sound propagation, and sound propagation in a refractive, turbulent atmosphere near an impedance ground. The coherence function of a sound field propagating in NBL was measured and compared with that predicted theoretically.

14. SUBJECT TERMS
Nighttime boundary layers, 3D spectra of temperature and wind velocity fluctuations, internal gravity waves, turbulence, quasi-wavelet models of turbulence, the sound scattering cross-section, the mean sound field, the coherence function.

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1. Statement of the problem studied

Studies of sound propagation in a turbulent atmosphere are important for both military and civil applications. First, these studies can significantly improve performance of U.S. Army acoustic sensors for source detection, ranging and recognition. Furthermore, many U.S. Army "smart" weapons rely on acoustic sensors. Second, civil applications of studies of sound propagation in a turbulent atmosphere include noise pollution near highways and airports, acoustic remote sensing of the atmosphere, and theories of waves in random media.

Most of the previous research in atmospheric acoustics has been devoted to studies of sound propagation in daytime boundary layers. In our two previous ARO projects, we developed theories of sound propagation in daytime boundary layers [see, G.H. Goedecke and V.E. Ostashev, ARO Project DAAH04-95-1-0593 (1995-1998); V.E. Ostashev and G.H. Goedecke, ARO Project DAAG55-98-1-0463 (1998-2001)]. However, studies of sound propagation and scattering in nighttime boundary layers (NBL) are also very important because Army sensors and smart weapons must operate during day and night. Note that nighttime conditions are usually very favorable to acoustic detection. The main gaols of this grant were development of 3D models of turbulence and internal gravity waves (IGW) in NBL and studies of sound propagation and scattering in NBL.

Specific tasks of the grant and their accomplishment are presented below in section 2.

2. Summary of the most important results

As a result of accomplishment of this grant, we developed a theory of sound propagation and scattering in NBL.

First, we obtained 3D spectra of temperature and wind velocity fluctuations due to IGW in moderately and very stable NBL. Also, we developed a 3D model of isotropic inhomogeneous turbulence in weakly stable NBL. Finally, we developed quasi-wavelet (QW) models of turbulent temperature and wind velocity fluctuations.

Then, the developed models of IGW, turbulence, and quasi-wavelets (QWs) were used to study sound propagation and scattering. We considered three different problems: scattering of sound, line-of-sight sound propagation, and sound propagation in a refractive, turbulent atmosphere near an impedance ground. Furthermore, the coherence function of a spherical sound wave propagating in NBL was measured and compared with that predicted theoretically.

The specific tasks of the grant and their accomplishment are as follows:

Task 1. 3D models of temperature and wind velocity fluctuations due to IGW in moderately and very stable NBL.

Accomplishment. This task was accomplished in Refs. [24-27]. First, we obtained the 3D spectra of temperature and wind velocity fluctuations due to IGW [24-26]. The normalized 3D spectrum of temperature fluctuations $\Phi_T(K_\perp, K_3)$ is shown in Fig. 1. Here, K_3 and $K_\perp$ are the components of the turbulence wave vector in the vertical and horizontal directions, respectively. In Fig. 1, K_0 is inversely proportional to the outer length-scale of the spectrum. It follows from the figure that $\Phi_T(K_\perp, K_3)$ reaches the maximum at $K_\perp = K_3 = 0$ and decreases along the $K_\perp$-axis much faster than along the K_3-axis; i.e. the spectrum is highly anisotropic. Second, we developed a model which predicts fluctuations in temperature and wind velocity due to one or several IGW in stably stratified NBL [27]. The model can be used for calculations of sound propagation through a snapshot of temperature and wind velocity fluctuations due to IGW.

Task 2. 3D models of isotropic, inhomogeneous, and intermittent turbulence in weakly stable NBL.

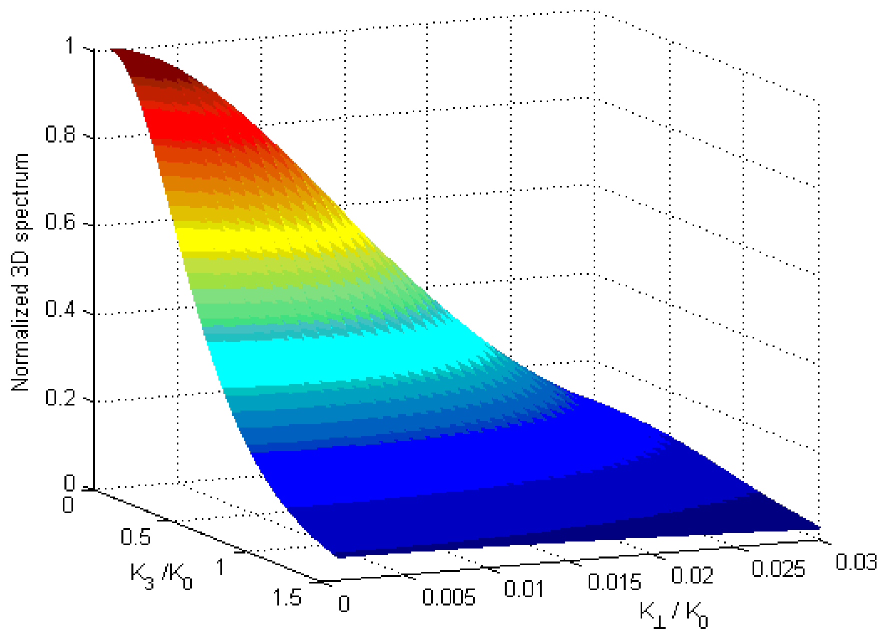

Figure 1: 3D spectrum of temperature fluctuations due to IGW.

Accomplishment. In weakly stable NBL, the 3D spectra of temperature and wind velocity fluctuations were modeled as isotropic, inhomogeneous von Kármán spectra, see Eqs. (1)-(8) in [3] or Eqs. (1)-(4) in [18]. In these equations, for the considered case of a weakly stable stratification, one should ignore terms containing the Monin-Obukhov scale L_o in the temperature spectrum and retain only shear-produced velocity fluctuations. The use of the von Kármán spectra of temperature and wind velocity fluctuations allows us to correctly describe the inertial subrange of turbulence and to realistically account for inhomogeneities in the energy subrange. Figure 2 from Ref. [3] depicts the von Kármán spectrum of temperature fluctuations (referred to as "simplified von Kármán") and a more general von Kármán spectrum of temperature fluctuations which has a Gaussian cutoff at large wavenumbers. The von Kármán spectrum of velocity fluctuations is shown in Fig. 3 obtained in Ref. [23].

It is well known that the turbulence in NBL can be intermittent, i.e. it can occur in bursts of activity. In [14,17], the intermittency of turbulence was modelled by assuming that the structure parameters of temperature and wind velocity fluctuations, C_T^2 and C_v^2, are random functions. Note that the considered above von Kármán spectra of temperature and wind velocity fluctuations are proportional to C_T^2 and C_v^2, respectively. Therefore, these spectra with random values of C_T^2 and C_v^2 provide 3D spectra of temperature and wind velocity fluctuations in weakly stable, intermittent NBL.

Task 3. Quasi-wavelet models of turbulent temperature and wind velocity fluctuations.
Accomplishment. The task was completed in Refs. [3,7,16,18,22,23]. During the reporting period, we have continued the development of QW models of turbulence which was started in our previous ARO project. QWs are localized, self-similar temperature or wind velocity eddies. The ensemble of QWs with many different sizes and properly chosen scaling laws resembles actual turbulence [3,7,16,18,23].

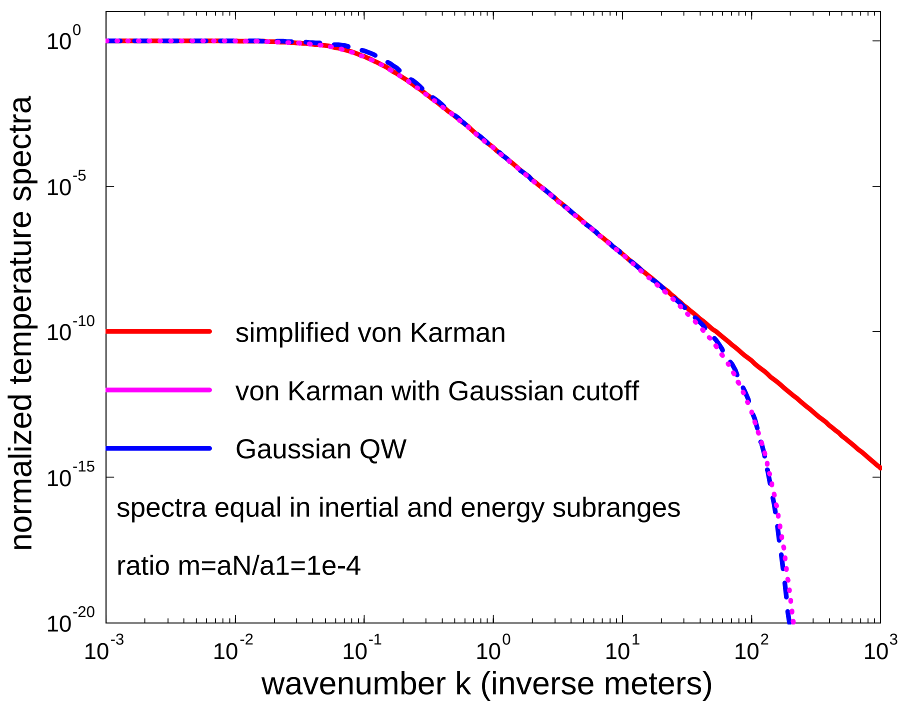

Figure 2: Spectra of temperature fluctuations.

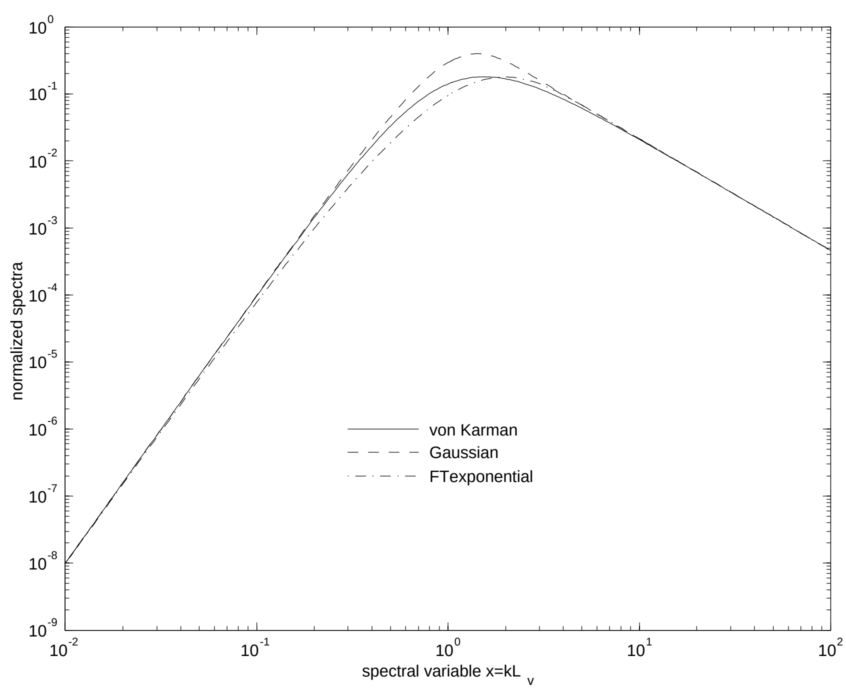

Figure 3: Spectra of velocity fluctuations.

The use of QW models in numerical and analytical calculations of sound propagation and scattering in a turbulent atmosphere can significantly simplify such calculations and be advantageous in comparison with other methods. During the project, we showed that isotropic turbulence with any physically "reasonable" spectra of temperature and wind velocity fluctuations can be modeled as an ensemble of QWs with specially chosen parent functions which determine the shape of QWs. In particular, we found the parent functions and, hence, QW models, which exactly result in the von Kármán spectra of temperature and wind velocity fluctuations, see Refs. [3,16,22,23]. This is an important result which can be considered as a phenomenological motivation for the von Kármán spectra. Furthermore, we found simple parent functions, gaussian and exponential (in the Fourier space), which yield the spectra that are very close to the von Kármán spectra, see Figs. 2 and 3. Finally, in [7], nonspherical QWs were used to model anisotropic, shear-driven velocity fluctuations. Note that wind shear is one of the mechanisms of turbulence in NBL.

Task 4. Sound scattering in a turbulent atmosphere.
Accomplishment. The task was completed in Refs. [1,2,8,10,12,19-21,24-26]. First, we derived the exact formula for the sound scattering cross-section per unit volume, σ, in a turbulent atmosphere [8,20]. This formula was derived from complete sets of linearized equations of fluid dynamics considered in [1,12,21]. In comparison with equations for σ known in the literature, the derived formula contains several new terms which describe sound scattering by atmospheric pressure fluctuations, the potential component of velocity, the cross-correlation between temperature and wind velocity fluctuations, etc. Using this formula, we studied sound scattering by atmospheric pressure fluctuations in NBL [8].

Second, we calculated the sound scattering cross-section σ for the case of sound scattering by temperature and wind velocity fluctuations due to IGW [24-26]. Figure 4 depicts the normalized σ as a function of $\theta - \theta_0$. Here, $\theta_0 = 85°$ and θ are the angles between the vertical axis and the directions of propagation of the incident and scattered waves, respectively. A sharp maximum in σ occurring at $\theta - \theta_0 = 0$ is a well known result in theories of waves in random media. In Fig. 4, there is also a second, much broader maximum which occurs at $\theta - \theta_0 = 10°$. This maximum is a new, interesting result which does not appear for the case of sound scattering by isotropic turbulence.

Third, the QW model of turbulent velocity fluctuations was used to study sound scattering behind barriers [2,19], and sound scattering into refractive shadow zone [10].

Task 5. Line-of-sight sound propagation.
Accomplishment. References [4,5,14,15,17,24-26] accomplish this task. For line-of-sight sound propagation, the most widely used statistical moments of a sound field are the mean sound field, the coherence function, and the structure functions of log-amplitude and phase fluctuations. In Refs. [4,5,14], general formulas for these statistical moments of plane and spherical sound waves propagating through inhomogeneous, anisotropic turbulence with arbitrary spectra of temperature and wind velocity fluctuations were derived. The derived general formulas were then used to calculate and study the statistical moments of a sound field for some important particular cases.

First, using these formulas, the mean sound field and the coherence function were calculated for the inhomogeneous von Kármán spectra of temperature and wind velocity fluctuations [4] and Mann's anisotropic spectral tensor of shear driven turbulence [14].

Second, the general formulas for the above-mentioned statistical moments of plane and spherical sound waves were used to calculate these statistical moments for the case of sound propagation through intermittent turbulence [14,17]. The calculations were done by assuming that the structure function parameters C_T^2 and C_v^2 are random functions along the sound propagation path as described in Task 2.

Third, the general formulas were used to calculate the mean sound field and the coherence function of a plane sound wave propagating in NBL with IGW [24-26]. Figure 5 from Ref. [24] shows the

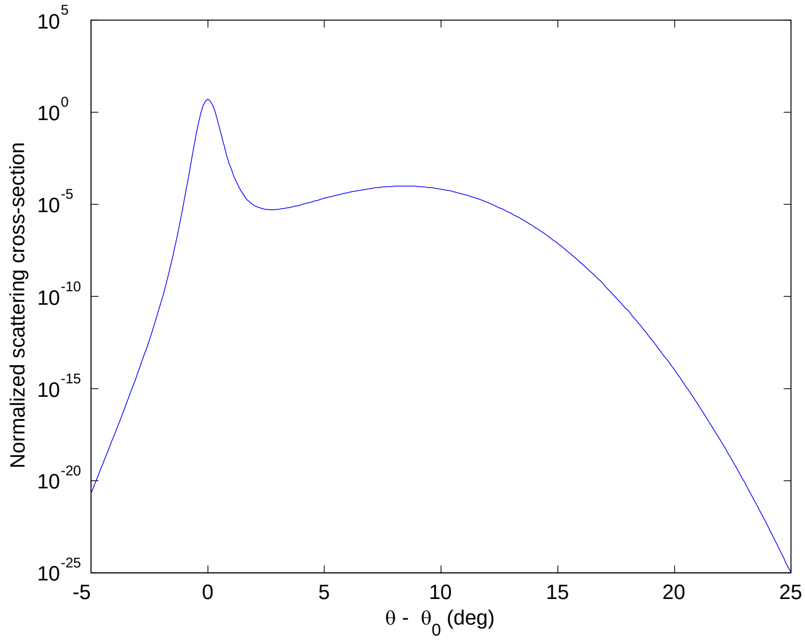

Figure 4: Normalized scattering cross-section due to sound scattering by IGW.

normalized coherence function $\hat{\Gamma}(x; y, z)$ versus the normalized separation between sensors. In figure, $\hat{\Gamma}(x; y, 0)$ is the normalized coherence function for the horizontal separation between two sensors along the y-axis, and $\hat{\Gamma}(x; 0, z)$ is that for the vertical separation between sensors along the z-axis. Different values of e_0 correspond to a different degree of anisotropy of IGW field. It follows from Fig. 5 that the coherence decays much more rapidly with increasing vertical separation between sensors than with increasing horizontal separation.

Finally, note that the state-of-the-art array for acoustic tomography of the atmosphere which is under construction by several organizations in the U.S. (ARO projects DAAD19-03-1-0104 and DAAD19-03-1-0341) will be based on measurements of travel times of line-of-sight sound propagation between different pairs of sources and receivers. Different theoretical aspects of this array were studied in [15].

Task 6. Combined effects of refraction, turbulence, and impedance ground on sound propagation.
Accomplishment. This task was accomplished in Refs. [1,6,9,11-13,21]. First, using some meteorological parameters, classification schemes for sound propagation in the nighttime and daytime atmosphere near the ground have been developed [6,11]. The transmission loss of sound propagation was classified in terms of these parameters.

Second, fast, accurate predictions of the sound pressure level in a refractive, turbulent atmosphere were developed based on an artificial neural network [9]. The neural network training parameters were the following: source and receiver height, the horizontal distance between source and receiver, the azimuthal direction of sound propagation, the static flow resistivity of the ground, the friction velocity, the turbulent sound speed scale, and a range of frequencies.

Third, new starting equations for calculations of sound propagation in a refractive, turbulent, and moving atmosphere were derived: a wide angle parabolic equation [13] and equations for finite-

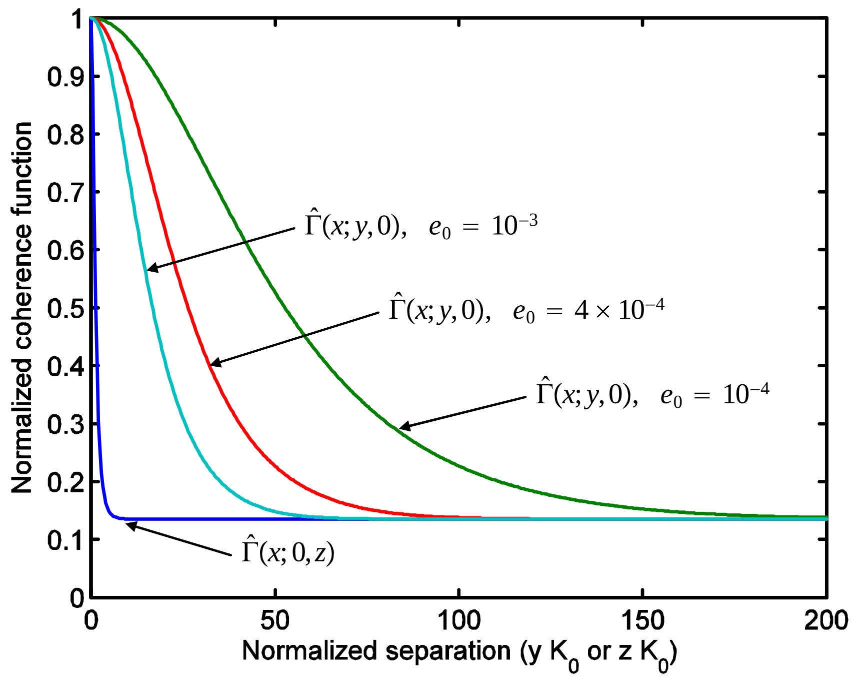

Figure 5: Normalized coherence function of a plane sound wave propagating through IGW field.

difference time domain calculations (FDTD) [1,12,21]. Note that FDTD techniques, which can provide the most accurate calculations of the sound field in complicated environments, have been under intensive development by Army scientists.

Task 7. Comparison of experimental results with theoretical predictions.
Accomplishment. This task was completed in Ref. [28]. First, the coherence function of a spherical sound wave and the spectra of temperature and wind velocity fluctuations were measured during 24 hours or even longer. The experimental results obtained were compared with theoretical predictions of the coherence function obtained in task 5.

Technology transfer

In accomplishment of this grant, we closely collaborated with the U.S. Army scientists: Dr. K. Wilson (CRREL), Dr. M. Mungiole (ARO), D. Marlin (ARO), and H. Auvermann (ARO). This means a direct transfer of the results obtained for needs of the CRREL and ARL. The Army scientists are coauthors in 25 of the total of 28 papers devoted to accomplishment of the grant, see the List of Publications below.

3. List of all publications supported under this grant:

3.1. Papers published in peer-reviewed journals

1. V. E. Ostashev, D. K. Wilson, L. Liu, D. Aldridge, N. P. Symons, and D. H. Marlin, "Equations for finite-difference, time-domain simulation of sound propagation in moving media and numerical implementation," J. Acoust. Soc. Am. **117** (2), 503-517 (2005).

2. D. K. Wilson, V. E. Ostashev, G. H. Goedecke, and H. Auvermann "Quasi-wavelet calculations of sound scattering behind barriers," Applied Acoustics **65**, 605-627 (2004).

3. G. H. Goedecke, V. E. Ostashev, D. K. Wilson, and H. J. Auvermann, "Quasi-wavelet model of von Kármán spectrum of turbulent velocity fluctuations," Boundary-Layer Meteorology, **112**, 33-56 (2004).

4. V. E. Ostashev and D. K. Wilson, "Coherence function and mean field of plane and spherical sound waves propagating through inhomogeneous anisotropic turbulence," J. Acoust. Soc. Am. **115** (2), 497-506 (2004).

5. V. E. Ostashev, D. K. Wilson, and G. H. Goedecke, "Spherical wave propagation through inhomogeneous, anisotropic turbulence: studies of log-amplitude and phase fluctuations," J. Acoust. Soc. Am. **115** (1), 120-130 (2004).

3.2. Papers published in conference proceedings

6. M. Mungiole, D.K. Wilson, and V.E. Ostashev, "Sound propagation classification schemes using atmospheric similarity parameters," *Proc. 11th Intern. Symp. on Long Range Sound Propagation*, Fairlee, VT (2004).

7. G.H. Goedecke, V.E. Ostashev, and D.K. Wilson, "Quasi-wavelet models of turbulent temperature and shear-driven velocity fluctuations," *Proc. 11th Intern. Symp. on Long Range Sound Propagation*, Fairlee, VT (2004).

8. V.E. Ostashev, D.K. Wilson, and G.H. Goedecke, "Sound scattering by pressure fluctuations and potential component of velocity," *Proc. 11th Intern. Symp. on Long Range Sound Propagation*, Fairlee, VT (2004).

9. M. Mungiole, D.K. Wilson, and V.E. Ostashev, "Predicting sound propagation in a turbulent atmosphere over a range of frequencies using an artificial neural network," *Proc. 11th Intern. Symp. on Long Range Sound Propagation*, Fairlee, VT (2004).

10. D. K. Wilson, V. E. Ostashev, and G. H. Goedecke, "Application of the quasi-wavelet turbulence model to atmospheric acoustics," *Proc. of the 18th International Congress on Acoustics (ICA2004)*, April 4-9, Kyoto, Japan, V. I, 125-128 (2004).

11. D. K. Wilson, V. E. Ostashev, and M. Mungiole, "Categorization schemes for near-ground sound propagation," *Proc. of the 18th International Congress on Acoustics (ICA2004)*, April 4-9, Kyoto, Japan, V. I, 361-364 (2004).

12. V. E. Ostashev, L. Liu, D. K. Wilson, M. L. Moran, D. Aldridge, and D. Marlin, "Starting equations for direct numerical simulation of sound propagation in the atmosphere," *Proc. 10th Intern. Symp. on Long Range Sound Propagation*, 73-81, Grenoble, France (2002).

13. V.E. Ostashev, Ph. Blanc-Benon, Júve, and L. Dallois, "Wide angle parabolic equation for sound waves in a refractive, turbulent atmosphere," *Proc. 10th Intern. Symp. on Long Range Sound Propagation*, 62-72, Grenoble, France (2002).

14. V.E. Ostashev and D.K. Wilson, "Sound propagation through inhomogeneous, anisotropic, and intermittent atmospheric turbulence," *Proc. 10th Intern. Symp. on Long Range Sound Propagation*, Grenoble, 236-248, France (2002).

15. V.E. Ostashev, A. Bedard, and A. Voronovich, “Array for acoustic tomography of the atmosphere,” *Proc. International Geoscience and Remote Sensing Symposium 2002*, Toronto, Canada, 862-864 (2002).
16. G.H. Goedecke, D.K. Wilson, V.E. Ostashev, and H. J. Auvermann, “Quasi-wavelet models for atmospheric turbulence,” *Proc. of the 15th Symposium on Boundary Layers and Turbulence, American Meteorological Society*, Wageningen, Netherlands, 394-397 (2002).
17. V.E. Ostashev and D.K. Wilson, “Line-of-sight sound propagation through intermittent atmospheric turbulence,” *Proc. of 9th International Congress on Sound and Vibration*, Orlando, FL (2002).
18. G.H. Goedecke, V.E. Ostashev, D.K. Wilson, and H. J. Auvermann, “Von Kármán spectra of temperature and velocity fluctuations,” *Proceedings of 9th International Congress on Sound and Vibration*, Orlando, FL (2002).
19. D. K. Wilson, V. E. Ostashev, G. H. Goedecke, and H. J. Auvermann, “Eddy-size decomposition of the scattering cross section using quasi-wavelets,” J. Acoust. Soc. Am. **114**, No 4, Pt. 2, 2441 (2003).
20. V. E. Ostashev and G. H. Goedecke, “Exact formula for the sound scattering per unit volume in a turbulent atmosphere,” J. Acoust. Soc. Am. **114**, No 4, Pt. 2, 2440 (2003).
21. V. E. Ostashev, L. Liu, D. K. Wilson, M. L. Moran, D. Aldridge, and D. Marlin, “Equations for direct numerical simulation of sound propagation in the atmosphere,” J. Acoust. Soc. Am. **113**, No 4, Pt. 2, 2312-2313 (2003).
22. G.H. Goedecke, V.E. Ostashev, D.K. Wilson, and H. J. Auvermann, “Quasi-wavelet models of sound scattering by atmospheric turbulence,” J. Acoust. Soc. Am., **111**, No 5, Pt. 2, 2351 (2002).

3.3. Manuscripts submitted, but not published

23. G. H. Goedecke, V. E. Ostashev, and D. K. Wilson, ”Quasi-wavelet models of turbulent temperature fluctuations,” Boundary-Layer Meteorology.
24. V. E. Ostashev, I. P. Chunchuzov, and D. K. Wilson, ”Sound propagation through and scattering by internal gravity waves in a stably stratified atmosphere,” J. Acoust. Soc. Am.
25.V. E. Ostashev, D. K. Wilson, and I. P. Chunchuzov, ”Scattering of sound by internal gravity waves,” *Forum Acusticum*, Budapest, Hungary (2005).
26. V. E. Ostashev, I. P. Chunchuzov, and D. K. Wilson, ”Scattering of sound and infrasound waves by internal gravity waves in the atmosphere,” *Acoust. Soc. Am. Meeting*, Vancouver, Canada (2005).

3.4. Manuscripts in preparation

27. V. E. Ostashev, D. K. Wilson, M. Mungiole, and I. P. Chunchuzov, ”The effects of internal gravity waves on sound propagation in NBL”.
28. V. E. Ostashev, S. Odintzov, V. P. Mamyshev, D. K. Wilson, and G. H. Goedecke, ”Experimental studies of the coherence function of a sound field in nighttime and daytime boundary layers”.

4. List of all participating scientific personnel

Dr. V.E. Ostashev
Dr. G.H. Goedecke

5. Report of inventions

None.